

A Network for Standardized Ocean Color Validation Measurements

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The Aerosol Robotic Network (AERONET) was developed to support atmospheric studies at various scales with measurements from worldwide distributed autonomous sun-photometers [Holben *et al.* 1998]. AERONET has now extended its support to marine applications through the additional capability of measuring the radiance emerging from the sea with modified sun-photometers installed on offshore platforms like lighthouses, navigation aids, oceanographic and oil towers. The functionality of this added network component called AERONET - Ocean Color (AERONET-OC), has been verified at different sites and deployment structures over a four year testing phase. Continuous or occasional deployment platforms (see Fig. 1) included: the Acqua Alta Oceanographic Tower (AAOT) of the Italian National Research Council in the northern Adriatic Sea since spring 2002; the Martha's Vineyard Coastal Observatory (MVCO) tower of the Woods Hole Oceanographic Institution in the Atlantic off the Massachusetts coast for different periods since spring 2004; the TOTAL Abu-Al-Bukhoosh oil Platform (AABP, shown through an artistic rendition in Fig. 1) in the Persian (Arabian) Gulf in fall 2004; the Gustaf Dalén Lighthouse Tower (GDLT) of the Swedish Maritime Administration in the Baltic Sea in summer 2005; and the platform at the Clouds and the Earth's Radiant Energy System (CERES) Ocean Validation Experiment (COVE) site located in the

Atlantic Ocean off the Virginia coast since fall 2005. Data collected during the network testing phase, confirm the capability of AERONET-OC to support the validation of marine optical remote sensing products through standardized measurements of normalized water-leaving radiance, L_{WN} , and aerosol optical thickness, τ_a , at multiple coastal sites.

Ocean Color Validation Requirements

The Coastal Zone Color Scanner (CZCS) mission of the early 1980s showed the capability of mapping the concentration of surface chlorophyll *a* as a proxy for marine phytoplankton biomass. Following this major achievement, since the mid-1990s several new Earth observing systems were put into space to increasingly support global studies on marine biogeochemistry and climate. Current systems providing continuous coverage of the globe are the Sea-viewing Wide-Field-of-view Sensor (SeaWiFS), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Medium Resolution Imaging Spectrometer (MERIS). These will be followed by the advanced Visible Infrared Imager Radiometer Suit (VIIRS) system that from 2009 will contribute to the operational monitoring of the Earth by collecting comprehensive data on oceans, land and clouds. A common requirement across all these systems is the need for highly accurate, frequent and globally distributed *in situ* observations to validate and additionally to benchmark derived products. This latter process is essential to support the creation of consistent time-series from different Earth observing systems.

The normalized water-leaving radiance, $L_{WN}(\lambda)$, at various center-wavelengths λ , is determined from top-of-atmosphere radiance corrected for the perturbing effects of the

atmosphere, and is the primary product generated from marine optical (i.e. ocean color) remote sensors. Higher level marine products, like the concentration of phytoplankton pigments or seawater inherent optical properties (i.e., absorption, scattering, back-scattering coefficients), are derived from L_{WN} data. The validation of this primary product usually relies on direct comparisons between satellite derived and *in situ* point observations.

Considering the difficulty of producing large individual data sets of *in situ* measurements representative of different marine trophic regimes, present validation programs combine into a single data set the field observations from many different and fully independent sources [Werdell *et al.*, 2003]. This impairs the quantification of measurement uncertainties which depend on the performance of different field instruments, on the use of diverse sampling methods, on the adoption of a variety of calibration sources and protocols, and lastly on the application of assorted processing schemes. Round-robin experiments [McClain *et al.* 2004] have shown that the former differences may be source of uncertainties above the maximum 5% value established for L_{WN} , thus reducing the effectiveness of validation processes. On the other hand, standardized networks of instruments continuously operating at different sites representative of distinct water types could provide large benefit to operational ocean color validation activities.

Autonomous Above-Water Radiometry

Advances in autonomous above-water radiometry have recently demonstrated the possibility for continuous deployments at fixed sites including the usually eutrophic coastal regions where in-water observations may be affected by bio-fouling perturbations.

Particularly relevant in this context is the extended capability of the CIMEL (Paris, France) CE-318 automated sun-photometer operated at the AERONET sites to perform marine radiometric measurements for determining L_{WN} in addition to the regular atmospheric measurements for the retrieval of τ_a [Hooker *et al.* 2000, Zibordi *et al.* 2004]. The instrument, called SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM), can autonomously perform multiple sky and sea radiance observations at programmable viewing and azimuth angles at various λ (i.e., 412, 440, 500, 555, 670, 870, and 1020 nm in the first instrument series, and, 412, 443, 490, 531, 551, 667, 870, and 1020 nm in the current release). The data transmission is made through the Data Collection System of geostationary meteorological satellites and allows for near real time data handling. Data processing requires site dependent inputs, in addition to measurement geometry and τ_a . Local wind speed observations, or alternatively model data from National Center for Environmental Prediction (NCEP), are used to minimize the perturbation effects of the surface. Chlorophyll *a* concentrations, iteratively estimated from L_{WN} using regional bio-optical algorithms, are additionally required for the removal of the off-nadir viewing angle dependence and effects of seawater light anisotropy on L_{WN} .

Results from SeaPRISM extensive deployments at the AAOT site [Zibordi *et al.* 2006], and additionally at the MVCO, AABP, GDLT and COVE sites, fully confirmed the possibility and relevance of expanding AERONET through AERONET-OC: a sub-network specifically supporting ocean color validation activities with highly consistent time-series of standardized measurements performed at different sites with a single

instrument type and measurement protocol, calibrated with identical reference source and method, and processed with the same code.

Data handling and application

AERONET-OC data, collected, processed and archived at Goddard Space Flight Center (GSFC) of the National Aeronautics and Space Administration (NASA), can be browsed and accessed under specified data policy through web interface (<http://aeronet.gsfc.nasa.gov>). Analogous to regular AERONET atmospheric products, the SeaPRISM products are available at three different levels. The data at Level 1.0 include all L_{WN} determined from sequences of sea measurements taken with viewing geometries minimizing the platform perturbations [Hooker and Zibordi 2005]. Level 1.5 data include screened L_{WN} corresponding to Level 1.0 products from measurement sequences not affected by: *i.* cloud perturbations as determined from triplets of direct sun irradiance measurements; *ii.* high variability in sea observations indicating elevated wave perturbations; or *iii.* high L_{WN} values in the near infrared suggesting the presence of obstacles in the optical path between the instrument and the water surface. Level 2.0 data refer to fully quality-assured L_{WN} , corresponding to Level 1.5 products originated from SeaPRISMs exhibiting differences smaller than 5% between the calibration coefficients determined before and after typical one-year deployment periods.

Figure 2 shows averages of L_{WN} quality-assured spectra from the AERONET-OC test sites. Notable are the differences in L_{WN} shapes and intensity across the various investigated regions which highlight a variety of bio-optical states suitable for comprehensive ocean color products validation. The scatter plots in Fig. 3 present match-

ups of MODIS and SeaPRISM L_{WN} (i.e., time corresponding satellite and *in situ* data) at various λ representative of the visible spectrum. While the number of AAOT match-ups included in this analysis was restricted to the first 50 of the 215 identified during the testing phase, the small number of match-ups produced for the other sites is explained by the brief deployment periods (mostly for AABP and COVE), and screening of cases affected by high seawater variability and land contamination (specifically for MVCO).

The comparison results summarized in Fig. 3 confirm that AERONET-OC data from sites representative of different bio-optical states can be a major complement to ship and mooring measurements for the validation of ocean color radiometric products. Further on, in agreement with accuracy requirements for the Global Earth Observation System of Systems (GEOSS), AERONET-OC strengthens the capability of tracing uncertainties in products from different remote sensing systems through time-series of highly consistent *in situ* data.

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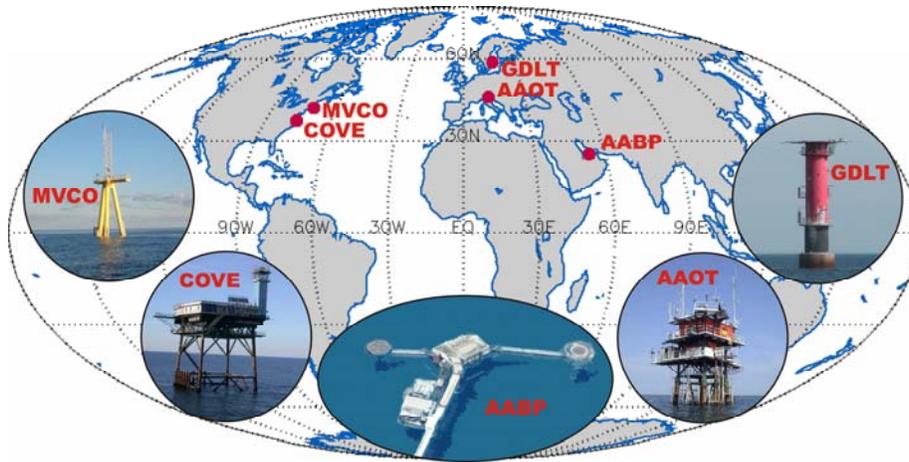


Figure 1. AERONET-OC sites during the network testing phase (2002-2005).

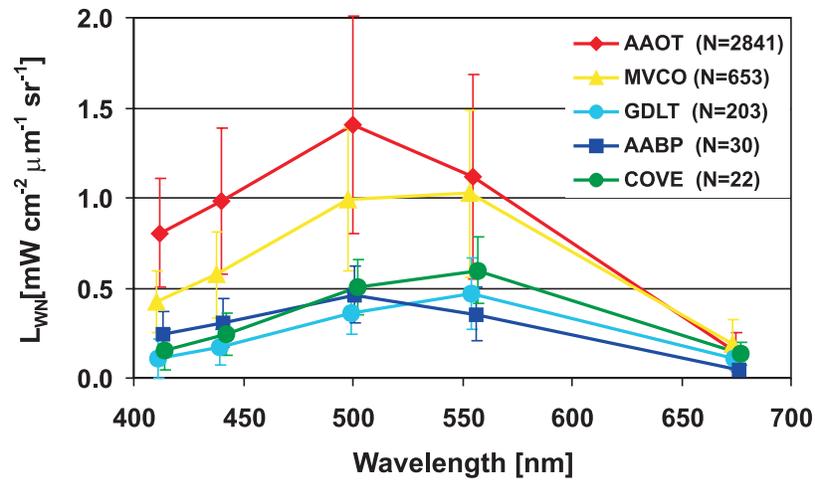


Figure 2. Average spectra of L_{WN} produced at the AERONET-OC testing sites. Error bars indicate \pm one standard deviation and N is the number of quality assured spectra. Center-wavelengths are slightly shifted for visualization purposes.

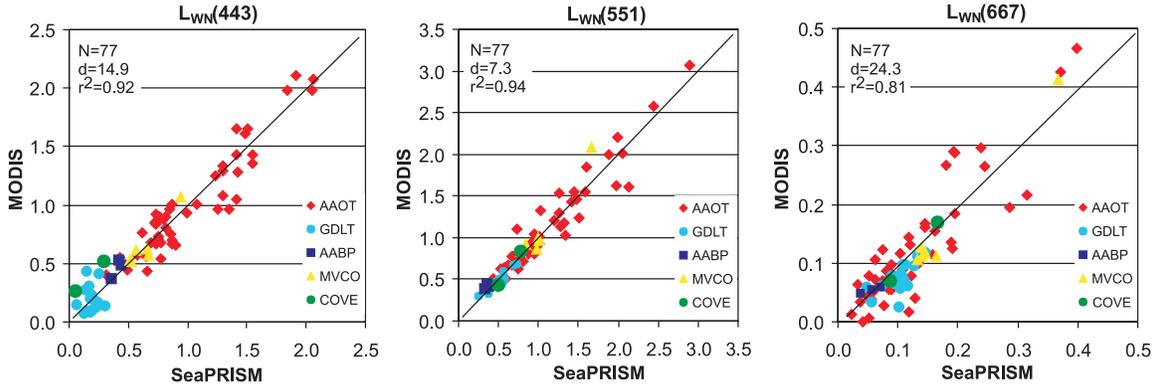


Figure 3. Scatter plots of satellite derived (MODIS-AQUA) versus *in situ* L_{WN} in units of $\text{mW cm}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$ at the 443, 551 and 667 nm MODIS center-wavelengths, for the AERONET-OC testing sites (N is the total number of match-ups, d is the median of the absolute percent differences and r^2 is the determination coefficient). The MODIS data were processed using the SeaWiFS Data Analysis System (SeaDAS, release 4.8). The match-ups are 50 for AAOT, 16 for GDLT, 3 for AABP, 6 for MVCO and 2 for COVE.